Lucired.cl:

a reduction pipeline for LUCIFER the infrared Multi Object Spectrograph at LBT

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Abstract

The present report describes the IRAF reduction package Lucired.cl, developed for the data reduction of the Multi Object Spectrograph (MOS) of the two LUCIFER near-IR instruments at the Large Binocular Telescope (LBT) on Mt. Graham, Arizona. The MOS mode will be the most used one for the two LUCIFER instruments, but will produce the most difficult data to deal with. The pipeline described here has been developed to automatize the reduction steps needed for the full exploitations of the data, such as distortion corrections, flat field, wavelength calibration, optimal sky subtraction, frame combination and flux calibration.

1 Introduction

The Large Binocular Telescope (LBT), a joint Italian, German and American project, is located on Mount Graham in the Pinaleno Mountains of southeastern Arizona and is a part of the Mount Graham International Observatory. The telescope design has two 8.4-meter mirrors mounted on a common base, hence the name "binocular". The collecting area is equivalent to an 11.8 meters circular aperture, greater than any other single telescope to date. Also, an interferometric mode will be available, with a maximum baseline of 22.8 meters for aperture synthesis imaging observations and a baseline of 15 meters for nulling interferometry.

LUCIFER (LBT NIR-Spectroscopic Utility with Camera and Integral-Field Unit for Extragalactic Research, Seifert et al. 2004) is a NIR spectrograph and imager (wavelength range 0.9 to 2.5 micron) for the LBT, working at cryogenic temperatures of less than 70K in the wavelength range $0.9\mu m$ to $2.5\mu m$. Two similar instruments are built by a consortium of five German institutes, to be mounted at the bent Gregorian foci of the two individual telescope mirrors. It is one of the first light instruments for the LBT, with LUCIFER1 starting the Science Demonstration Time in December 2009. The second copy of the instrument will follow in spring 2011.

The instrument will be one of the first efficient NIR multi-object spectrographs at a large 10m class telescope, and therefore will be well suited especially for the exploration of the astrophysical properties of high-redshift objects. Important information will be also obtained from imaging and photometry in the NIR (e.g. for photometric redshift determination or optical rest frame morphology with AO). Moreover, the imaging is needed to obtain preimaging data to prepare the MOS programs. Even though the LUCIFER design is aiming mainly at imaging and spectroscopy of very faint point sources and slightly extended objects with high efficiency, it will also be very powerful for many other scientific programs in extragalactic and stellar astrophysics and in interstellar matter research. Examples might be the spectroscopy of faint very red stars, brown dwarfs and circumstellar and extragalactic disks, as well as studies of star forming regions and very reddened objects.

In this report we will first describe the LUCIFER instrument and the MOS unit in section 2, the pipeline architecture in section 3, and the various tasks of the package in section 4.

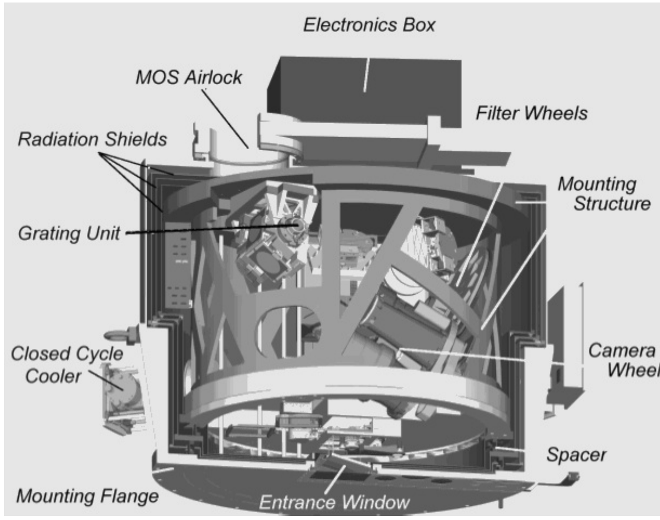

Figure 1: Layout of the LUCIFER instrument.

2 LUCIFER and the MOS unit

Three exchangeable cameras are available for imaging and spectroscopy: two of them are optimized for seeing-limited conditions, while a third camera for the diffraction limited case will be used with the LBT adaptive secondary mirror working. The instrument is capable of the following observing modes:

- Direct imaging over a $4' \times 4'$ field of view (FOV), seeing limited
- Diffraction limited AO assisted imaging over a $0.5' \times 0.5'$ FOV
- Longslit spectroscopy, seeing and diffraction limited
- Multi-object spectroscopy with slit masks over a $4' \times 3'$ FOV

The opto-mechanical layout of the instrument is shown in Fig. 1. Three cameras are available for the various observing modes. Up to 30 filters can be stored in two wheels which are located in the convergent beam of the camera just in front of the detector. The instrument is cooled by two closed cycle coolers (CCC) and will work below 77 K, while the detector can be independently cooled down to 60 K. At the pupil position a fold mirror for imaging and up to three gratings for spectroscopy are selectable on a wheel. Every mirror/grating has its own optimized cold stop attached to it.

Three cameras with different image scales are remotely exchangeable. One camera (called N30) is optimized for observations at the diffraction-limit of the telescope. The image scale is adapted to the

Mode	Seeing Limited		Diffraction Limited
Camera	N3.75	N1.8	N30
FOV	4 x 4 arcmin	4 x 4 arcmin	0.5 x 0.5 arcmin
f_{Coll}	1500 mm	1500 mm	1500 mm
f_{Cam}	375 mm	180 mm	3000 mm
N_{Cam}	3.75	1.80	30
f_{eff}	30940 mm	14850 mm	247540 mm
Scale	0.12 arcsec/pixel	0.25 arcsec/pixel	0.015 arcsec/pixel
Beam diameter	102 mm	102 mm	102 mm
Slit length	up to 4 arcmin	up to 4 arcmin	$\leq$ 0.5 arcmin
R_{lim}	10000 (0.24 arcsec slit)	5000 (0.50 arcsec slit)	
FSR (K band)	0.22 μ	0.46 μ	
R_{lim} (K)			20600 (0.13 arcsec slit)
R_{lim} (H)			28200 (0.10 arcsec slit)
R_{lim} (J)			37100 (0.08 arcsec slit)

Figure 2: Basic data for the seeing and diffraction limited modes.

Parameter	Imaging	Spectroscopy
Scale	0.25 arcsec/pixel	0.25 arcsec/pixel
FOV	4 x 4 arcmin^2	4 x 3 arcmin^2
Resolution		500... 5000
Comments	aquisition only narrowband filters	full band coverage zJHK Longslit and MOS
Scale	0.12 arcsec/pixel	0.12 arcsec/pixel
FOV	4 x 4 arcmin^2	4 x 3 arcmin^2
Resolution		1000... 10000
Comments	broad and narrow band	Longslit and MOS
Scale	0.015 arcsec/pixel	0.015 arcsec/pixel
FOV	0.5 x 0.5 arcmin^2	0.5 x 0.5 arcmin^2
Resolution		4000... 40000
Comments	FOV limited by isoplanatism	'Longslit'

Figure 3: Summary of the available instrument modes.

Airy disk in the J-band. An atmospheric dispersion corrector (ADC) will be inserted in front of the telescope focus for imaging and spectroscopy in the zJH bands. For spectroscopy in this mode, a slit viewer which is feed by a small mirror on the slit mask can be switched into the beam in front of the focus. The other two cameras (called N1.8 and N3.75) are used for imaging and spectroscopy under seeing-limited conditions. The N1.8 camera is optimized mainly for spectroscopy and can cover the full wavelength range of each photometric band (zJHK) at a spectral resolution of $\sim$ 5000 (but see the summary of the available grisms in Fig. 5), allowing for effective OH suppression. The N3.75 camera is optimized for imaging (broad-band and narrow-band), but can also be used for spectroscopy with a resolution of up to 10000. The characteristic data for using the different cameras are summarized in Fig. 2. The capabilities of the various instrument observing modes are given in Fig. 3.

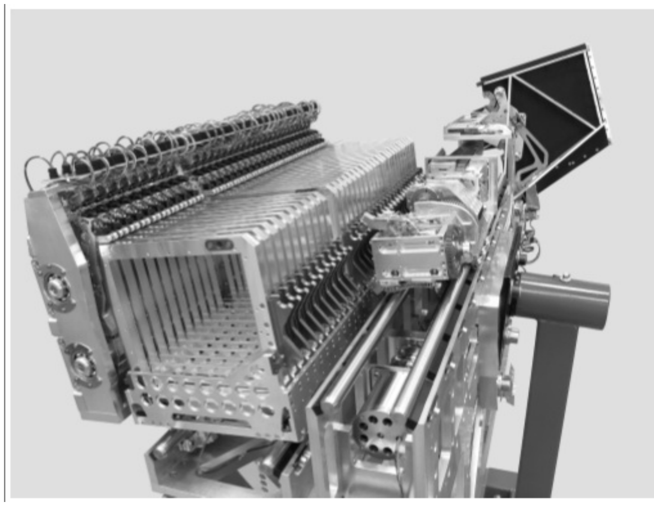

Figure 4: The MOS unit attached to the integration mount, seen from the location of the focal plane unit which is mounted separately on the LUCIFER structure and is not included here. From left to right: the mask retainer with 33 independent locking mechanisms; the stationary and the exchangeable mask cabinets with 10 and 23 slots respectively, filled with empty mask frames (a gap in the mask sequence indicates the border between the cabinets); the MOS robot in the position to grab a mask; the rails for the robot translation and the translation motor in the foreground; the shutter to close the breakout for the mask cabinet in the radiation shield in the background (from Mandel et al. 2008).

Up to 33 exchangeable masks are available for longslit or multi-object spectroscopy (MOS) over the full field of view (FOV) of $4' \times 3'$. There will be a set of 'standard' longslit and field stop masks as well as 23 freely configurable masks for MOS and e.g. coronography. However, seeing-limited multi-object spectroscopy (MOS) with multi-slit masks will be the most frequently used observing mode of LUCIFER, given the scientific impact of such an instrument (see e.g. Forster Schreiber 2007). For each observation in this mode, a dedicated slit mask has to be placed by a robot in the telescope focal plane. This exchange of slit masks between a storage cabinet and the focal plane as well as the replacement of the masks is handled by the so-called MOS unit, which consists of a subsystem integrated into the LUCIFER cryostat and of two auxiliary cryostats required for mask replacement with LUCIFER at its operating temperature, so that the complete mask cabinet can be exchanged through this airlock system while the instrument is cold. A detailed description of the MOS unit and of the

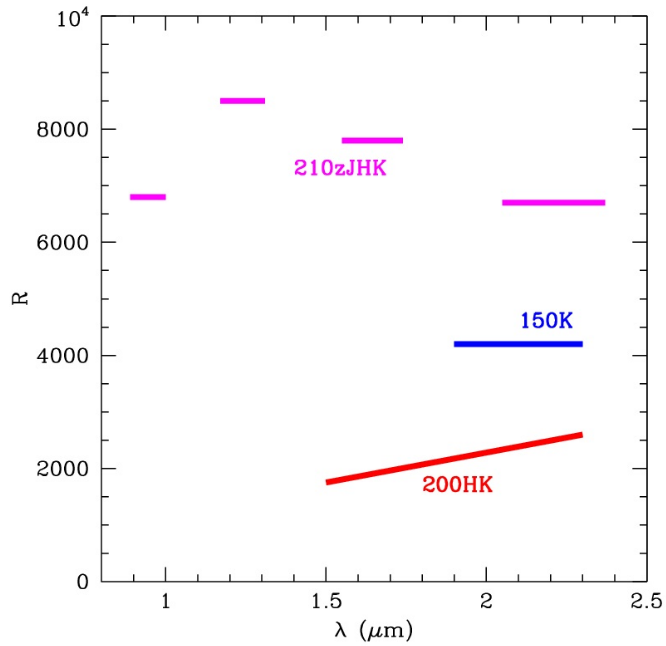

Figure 5: Summary of the available grisms for LUCIFER (MOS and longslit). The plot shows the wavelength coverage of the different grisms versus the spectral resolution R, using a 0.5” slit and the $N1.8$ camera.

robot can be found in Hofmann et al. (2004).

3 The pipeline

We have developed a data reduction pipeline for the Lucifer MOS mode, that can be used also for longslit data reduction. The pipeline is written in the SPP programming language for IRAF (Image Reduction and Analysis Facility, Tody 1986), a general purpose software system for the reduction and analysis of scientific astronomical data. This choice has the advantage that the IRAF package already includes many useful libraries for image and spectra manipulation and calibration, that can be used or modified for LUCIFER data reduction.

The lucired.cl pipeline can be installed in IRAF, so that it is accessible as a normal IRAF package. In this way the user will not need to define the tasks for the reduction each time at the login in the IRAF environment. When the pipeline package is properly installed, all the IRAF packages and scripts used in the reduction are automatically loaded, and the different lucired.cl tasks are accessible directly

Figure 6: Login prompt of the lucired package in IRAF

with their help page just by typing *lucired* at the IRAF prompt (see Fig. 6).

A small help for each of each task is accessible by typing *help "taskname"*. This command displays a small description of the task, an example, and an explanation of all the parameters that can be changed by the user to optimize that particular reduction step. Each of the tasks can be called from IRAF according to the syntax showed in its own help, or from the parameters summary accessible by typing *epar taskname*. This summary allows the user to change interactively the input parameters, and to run the task typing *:go*.

The optimal sky subtraction, described in detail in section 4.8, is instead performed using an IDL script. This script is automatically called from IRAF, but this requires that both IRAF and IDL are installed on the user system.

luciall.cl is a special task, not described below, that allows a complete reduction of the data with a single command. It should be used with caution, as it is not possible to check all the intermediate steps of the reduction, mainly to re-reduce some data with different parameters or for a quick first look at the data, e.g. while observing at the telescope. All the other tasks are described in detail in the following sections.

In order to run the pipeline, all the relevant data (both calibrations and science frames) from a single night must be in the same directory. The pipeline expects that this is the same home directory from which the different tasks are called.

4 Tasks description

4.1 lucilist

This task automatically creates the lists of flats, waves, darks, pinhole frames and science frames to be used by the following tasks to identify the different classes of frames. It reads in each fits file header the frame type, and adds that file to the proper list. All the data, both calibrations and science frames, must be in the same directory where the task has been run. It creates in output the different "$list.*.txt$" files.

4.2 luciflat

This task creates the masterflat, masterdark and bad pixel mask. The master flat is created using in input all the flat field frames (see Fig. 7), both with high and low signal, obtained with an uniform illumination of the detector with the calibration lamps. The flat field frames are combined to create a masterflat with higher signal to noise, to be used to correct the different response of the different pixels on the frame. For this purpose, the masterflat frame is normalized over the regions occupied by the spectra, ignoring the inter-slits regions.

In the same way a masterdark is created from the single dark frames. Both the flats and the darks are used to locate pixels deviating more than N sigma from their neighbors, to create a bad pixel map. The use of a combination of darks and flats to create the mask allows to better locate deviating pixels with both too high or too low value. The $masterflat.fits$, $masterdark.fits$ and *bpmtot.pl* frames are created in output. The relevant parameters are:

- *lowlist*: file containing a list of low-signal flat field images (even just a single frame)
- *highlist*: file containing a list of high-signal flat field images (even just a single frame)
- *darklist*: file with the list of dark images (even just a single frame)
- *lowthr*: Lower sigma threshold for bad pixel rejection
- *highthr*: Higher sigma threshold for bad pixel rejection

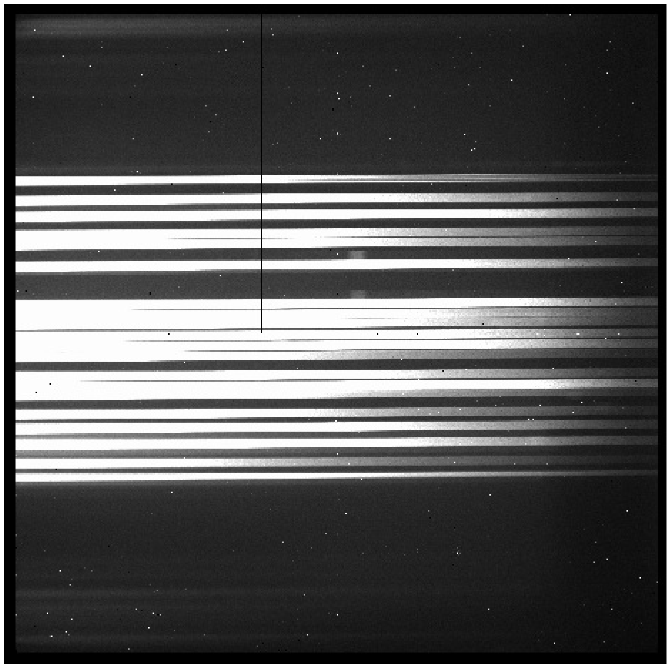

Figure 7: Example of a flat field frame. The white, high signal stripes mark the position of the various slits on the frame.

4.3 lucidist

The task is used to calculate the slit distortion on the frame in the spectral direction. The spectra from each slit are in fact usually slightly curved by few pixels, due to distortions in the instrument. To evaluate these distortions a special calibration mask is used, a sieve mask with pinholes in the center of the frame. A spectroscopic flat field obtained with this mask (see Fig 8) is used to trace the distortion along the spectral direction with the IRAF identify task. The best fitting legendre polynomial solution is stored in a database. The tunable parameters are:

- *distimg*: name of the spectroscopic sieve mask flat field frame
- *distdat*: name of output distortion database to be used by the following tasks
- *sepmin*: minimum separation between two pinholes
- *minlim*: threshold flux for a pinhole spectra to be selected
- *interact*: (yes/no) if yes, the distortion fit is checked interactively (press q to exit and accept, :xorder N :yorder N to change fitting

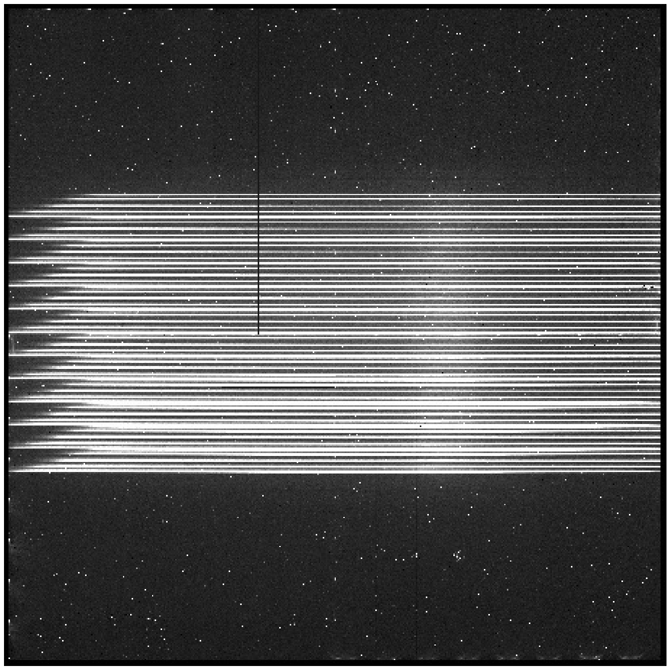

Figure 8: The spectroscopic sieve mask used to trace the distortions in the spectral direction.

order, ? for more option once the interactive windows pops up)

4.4 lucicorr

This tasks first removes eventual cosmic rays from the science frames, using the van Dokkum (2001) algorithm LACOS. This is a very efficient algorithm based on Laplacian edge detection, that identifies cosmic rays of arbitrary shapes and sizes by the sharpness of their edges and is able to reliably discriminates between poorly sampled point sources (or sky lines in our case) and cosmic rays.

The task then applies the flat field correction to all the science and wavelength calibration frames, using the masterflat frame created, and corrects for the slit distortion along the spectral direction using the distortion solution fitted by the previous task. It also accounts for bad pixels with linear interpolation between neighbors thanks to the bad pixel mask. The corrected wavelength calibration frames with the lamps lines are finally combined to create a "masterwave" frame. The output results are therefore a set of corrected (flat-fielded, spectral distortion, bad pixels and cosmic rays removed) science frames, and the *masterwave.fits* image. The parameters are:

- *scilist*: list of science images
- *wave*: list of arc lamps (on and off)
- *mflat*: masterflat image
- *mdark*: masterdark image
- *distdat*: Name of the distortion database created by lucidist
- *distfit*: Name of the distortion fit in the database, i.e. the name of the spectroscopic sieve mask image used to evaluate the distortion
- *bpcorr*: (yes/no) if yes corrects the bad pixels by linear interpolation
- *cosmcorr*: (yes/no) if yes removes the cosmic rays with the LA-COS algorithm

4.5 lucitran

This task calculates the coordinates transformation between millimeters on the physical mask to pixels on the final frame. This coordinates transformation is needed to recover the exact position of the slit on the frame, starting from the position in *mm* stored in the header and used to cut the slits on the mask. The transformation is measured using a special calibration pinhole mask (see Fig. 9), which consist in a grid of pinholes at known distance and known position in millimeters. The outer part of the grid consists in pinholes at a distance of 5 *mm*, while in the finer inner grid the distance is 2.5 *mm*. After applying to the pinhole frame the same distortion correction used for the science frames and calculated by the lucidist task, the task asks the user to select manually on the frame 12 pinholes, i.e. the four corners of both the outer and inner grid, as well as the center pinhole of the outer columns and rows. These points are used as reference to evaluate the transformation using the IRAF geomap task. The derived transformation is then applied to the whole set of pinholes, to check that the expected position on the frame corresponds to the actual one, and displayed to the user. The transformation parameters are stored in a database to be used by the following tasks.

This calibration and this reduction step are not required if a file with the slit position in (x $y1$ $y2$) format is available, where $y1$ and $y2$ are the lower and upper pixel of each slit and x the position of the central wavelength in the spectral direction. It creates in output a file with the slit positions. The parameters are:

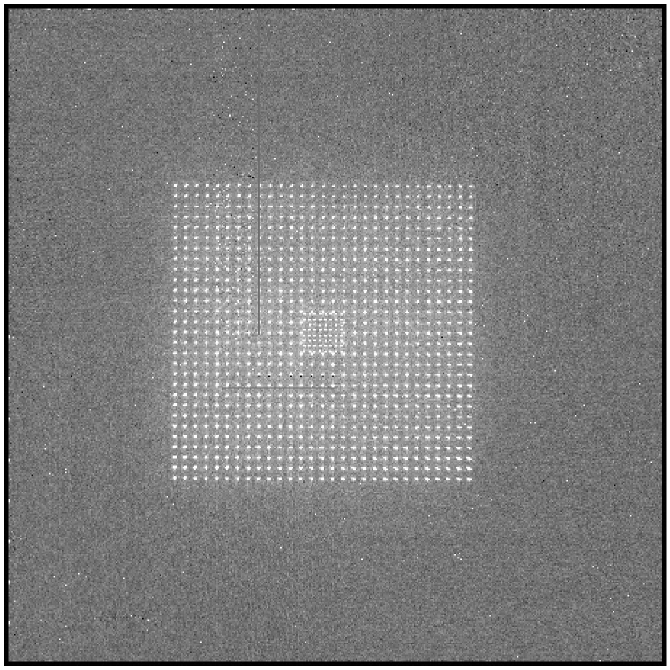

Figure 9: The pinhole mask used to calculate the millimeters to pixels transformation.

- *pinimg*: pinhole image name
- *outdat*: name of the output transformation database
- *distdat*: name of the distortion database created by lucidist
- *distfit*: name of the distortion fit in the database , i.e. the name of the spectroscopic pinhole sieve mask image used to evaluate the distortion
- *interact*: (yes/no) interactively select the pinholes: the image of the pinholes is displayed, and the routine asks you to click with SPACE followed by Control-D on 12 of the pinholes (the four corners, the four central pinhole in the first and last row and column, and the four corners of the central finer pinholes)
- *pixmmfile*: if interact is NO, a file with the coordinates in pixel and mm of selected pinholes is required (xpx ypx xmm ymm). If interact is YES, an output file with the coordinates of the selected pinholes with this name is created

4.6 lucicuts

At this stage all the corrected MOS frames are cut into single slits. The pipeline is in fact dealing with the multi-slits on the frame by cutting them in single smaller frames and reducing them as normal longslit datasets. This approach can be accceptable, as the number of slit is usually limited to $\sim 10 - 20$.

The task creates a slit fits file for each slit in each frame, attaching to each new file the information about the corresponding slit position and target name stored in the header of the original frame. The target name is saved in the header of the new file created for the single slit, while the slit name and the original frame name are preserved also in the new file name. The cutting positions are given by the position in millimeters in the header, converted in pixels using the transformation from the lucitran task, or by a file with the slit coordinates in pixels created by the user. It also creates in output a file with the slit position, if this was not provided in input. The parameters are:

- *listsci*: list of corrected science images to be cut
- *listarc*: list of corrected arcwave frame to be cut
- *databslit*: Name of the mm-pix transformation database created by lucitran
- *slitfile*: Name of the file with slit coordinates (x ylow yhi): if specified, the parameter *databslit* is ignored, no transformation is computed and the slits are cut using only the information on this file
- *yshift*: y axis shift to be added to the computed slits coordinates (e.g. if a shift between imaging and spectroscopic modes is detected, to be evaluated during daytime calibration)

4.7 luciwave

The task calculates and applies the wavelength calibration. It first searches and identifies, automatically or interactively, the lamp features in the masterwave file (see Fig. 10) of each of the slits in the original frame. The lines in these exposures are obtained from Argon and/or Xenon calibration lamps. The task then fits a wavelength solution to the detected lines, using a Ar/Xe line list provided (in the *utils* directory of the lucired.cl package), a guess of the central wavelength derived from the x position of the slit on the frame and dispersion guess according to the camera/grism combination. It also corrects for

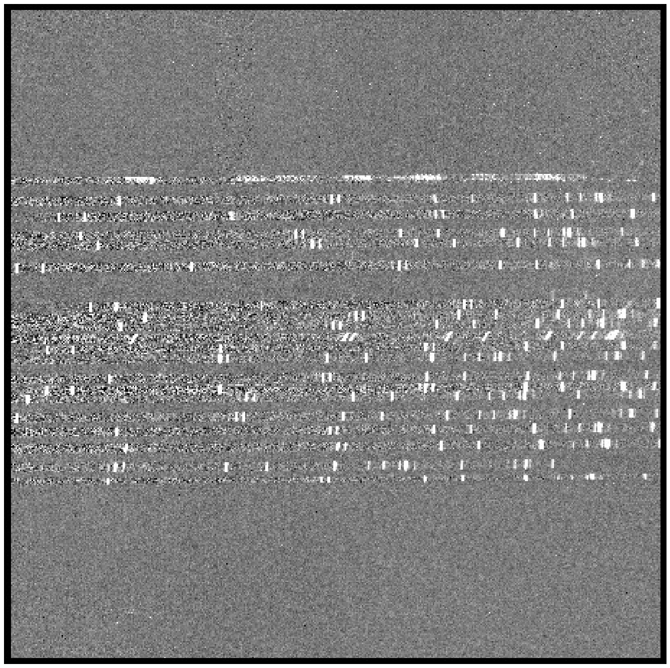

Figure 10: Example of "masterwave" file. The calibration lines from the Argon lamp are prominent in the different slits.

the distortion in the spatial direction making the lines straight. It uses the IRAF tasks autoidentify and reidentify for these purposes.

Finally, it applies the best fitting wavelength solution and spatial distortion correction to the science data and to the wavelength calibration frames themself. The wave-corrected arc frames are displayed to the user, to check the wavelength solution: all the lines should be vertical and at the same pixel in all the slits. The parameters that can be changed by the user are:

- *scilist*: list of original (before correction) science images names
- *linefile*: text file with a list of wavelengths in Angstrom of the lamp lines for the corresponding lamp/filter/camera setting
- *markwav*: original masterwave image
- *slitcoo*: position of the slits in px (e.g. the file called $slit_pos_px.txt$ created by the lucicut task)
- *linthres*: in order for a line center to be measured, the range of pixel intensities around the line must exceed this threshold.

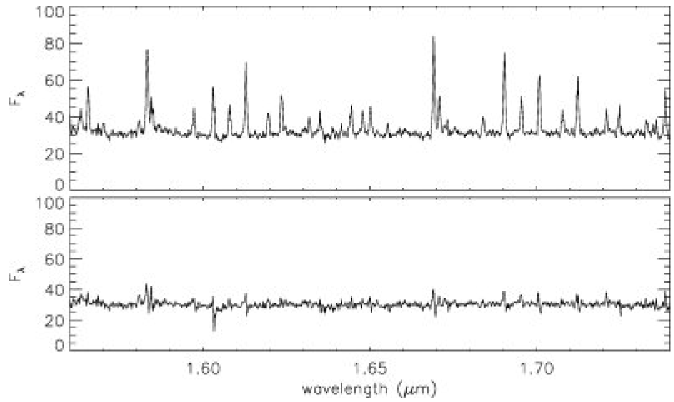

Figure 11: Top: Spectrum of a sky subtracted 5 min SINFONI exposure showing residual OH lines after subtracting a sky frame taken immediately afterwards. The flux in these residuals is only $\sim 3\%$ of the original OH emission, but is still significant. Bottom: the same two frames are subtracted using the scaling procedure described in the text. The spectra are of NGC 3783 and in both cases were extracted within a 0.5-arcsec aperture centred slightly off the galaxy nucleus. (From Davies 2007)

- *ntarfeat*: number of spectral lines from the target spectrum to use in the pattern matching
- *intercat*: (yes/no) if yes, the identification of the features on the masterwave slits is shown, allowing interactive fitting of a wavelength solution. A wrong id can be deleted pressing d on it, and the wavelength of a missing feature can be added pressing m on it and typing the wavelength in Angstrom. If something is changed, press l to relocate the lines and f to refit. q to exit the interactive window for that slit

4.8 lucicomb

We are now ready to leave the calibration frames to work on the corrected science frames. Each frame has been in fact cleaned of bad pixels and cosmic rays, flat fielded, distortion corrected both in the spectral and in the spatial direction, and wavelength calibrated. Each slit of the frame has been cut so that we can work with several longslit-like frames. Before using our data to make some good science, we have to remove the sky background. This is a very critical step in the near-IR, especially due to the strongly varying OH airglow emission typical of near-infrared spectra.

Historically, the need to subtract out the strong and variable OH airglow emission lines from 1 to 2.5 μm spectra has imposed severe restrictions on observational strategy. For MOS spectroscopy, the two possibilities are to observe blank sky frames at regular intervals, or to nod along the slits to sample the sky background. However, even this does not usually provide sufficient compensation if individual exposure times are longer than 2-3 minutes due to (1) changes in the absolute flux of the OH lines, (2) variations in flux among the individual OH lines and (3) effects of instrumental flexure which can lead to 'P-Cygni' type residuals. To improve the subtraction of the sky lines we adopt the Davies (2007) technique, that takes all of these effects into account and also improves background subtraction between the OH lines. The basis of the technique is to find a scaling as a function of wavelength, that can be applied to a sky spectrum in order to match it optimally to the sky background in an object spectrum. The scaling function is applied to the sky spectrum, creating a modified sky, which is then subtracted from the object cube, conveniently solving the issue of the variable spectral-line profiles (see Fig. 11). The sky subtraction with this algorithm is performed with an IDL script, $luci_skysub.pro$, which is called automatically by IRAF. However, the user should check to have IDL installed and working to have a proper sky subtraction and OH lines removal.

The task finally combines the sky-subtracted science slits from each frame. Both on-off observing mode and on slit nodding are supported, with the relative offsets between each frame and the observing mode derived from the header or from a provide file. The final 2D frames are displayed, to check the obtained spectra in a single image called "*showslits.fits*", with the same wavelength corresponding to the same position on the frame for each of the slits. The parameters for this task are:

- *scilist*: list of original science images names
- *nslits*: number of slits in each frame
- *headoff*: (yes/no) if yes, it reads in the header the offset between different frames to combine them, if no looks for a file to read the offsets to apply
- *fileoff*: file containing the offsets in y between the different frames. Frame one has 0, the others the relative offsets in pixels from the first one.

4.9 lucishow

This routine is only called by the luciwave and lucicomb tasks. It shows a list of wavelength calibrated slits or 2D spectra on a single frame, with the same wavelength scale. The parameters are:

- *inlist*: list of slits to be shown
- *outimage*: name for the output image

4.10 lucifcal

An additional task for automatic flux calibration and Telluric correction is currently under development and testing. It will be available in the next version of the pipeline.

5 Conclusions

We have developed a data reduction pipeline for the LUCIFER instrument MOS and longslit modes. The pipeline is written with the IRAF SPP programming language, and takes advantage of the large IRAF libraries of routines for astronomical data handle. The pipeline incorporates distortion correction both in the spatial and spectral direction, flat field correction, bad pixels and cosmic rays removal, wavelength calibration and optimal sky subtraction for improved OH lines removal. The last one is in fact a fundamental step in the reduction of near-IR spectra, where the OH features are particularly strong and concentrated. It has to be noted, however, that even if the sky subtraction routine is able to remove most of the residuals of the sky lines, the Poisson noise in the line regions is still much higher than in the inter-lines parts of the spectra, severely affecting the possible analysis.

The pipeline cuts each of the slit of the mask in order to work with several ($\sim 10-20$) single longslit sub-frame. The final products are 2D combined and sky subtracted spectra. An extraction tool is currently not implemented, as LUCIFER is expected to work mostly with high-z sources with faint continuum, making difficult to automatize the spectra extraction. A flux calibration routine is instead currently under development and will be available for the next version of the pipeline.

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